Bone Stress Injuries

Because of their insidious onset and overlap of clinical signs and symptoms, stress fractures and other bone stress injuries present a diagnostic challenge for clinicians. Magnetic resonance imaging (MRI) can be used to efficiently detect and grade stress fractures and other bone stress injuries, allowing appropriate and timely treatment (Fredericson et al., 1995). This unit outlines basic MR protocols for evaluating the most common bone stress injuries including those of the tibia, femoral neck, femoral shaft, metatarsal, and navicular bone. The protocols concentrate on the lower extremity, as the majority of stress injures occur in this region (Hulkko and Orava, 1987; Matheson et al., 1987). These protocols were developed using a 1.5 T system (Signa, General Electric Medical Systems). Detection of subtle changes in bone marrow or periosteal signal (edema) is essential in the evaluation of stress injury. By experience, the authors have found high field strength systems to be excellent in this regard, therefore, are preferred over low and mid field strength magnets for this application. However, the sequences described here could be adapted to low or mid field scanners using STIR (short tau inversion recovery) sequences to acquire the T_2-weighted images. This technique would require longer scan times and lower resolution matrices.

TIBIAL STRESS INJURIES

BASIC PROTOCOL 1

Stress injuries are attributed to running more often than any other athletic activity, and the tibia is the most common site of stress injury among runners (Hulkko and Orava, 1987; Matheson et al., 1987). Patients usually complain of pain with activity, which worsens over time if the activity is continued. Eventually, pain may occur with routine ambulation or at rest (Fredericson et al., 1995). MRI evaluation is focused on the area of signs and symptoms.

Four primary sequences are utilized for this protocol: (1) coronal T_1-weighted spin echo; (2) coronal T_2-weighted fast spin echo (FSE); (3) transverse T_1-weighted spin echo; and (4) transverse T_2-weighted FSE. The approximate amount of time needed to complete this protocol is 30 min.

Table A24.1.1 outlines the equipment needed to perform this examination. Cardiac and respiratory gating are not used and contrast agents are not needed.

NOTE: Be sure that technologists and nurses have immediate access to any emergency equipment that may be relevant to a given study, or that may be needed for a particular patient, such as crash carts or oxygen.

Set up patient and equipment

1. Interview the patient to ensure that he or she has no contraindications such as cardiac pacemakers or other implants containing ferromagnetic materials. Also, be sure to find out if the patient has any health conditions that may require the presence of

Table A24.1.1 Equipment Parameters for Stress Injuries

Coil type	Extremity or torso phased array
Gradient coil strength	22 mT/m (or whatever the system permits)
Cardiac gating	No
Respiratory gating	No
Use of contrast agents	No

Contributed by Gabrielle Bergman and Timothy R. Jones
Current Protocols in Magnetic Resonance Imaging (2001) A24.1.1-A24.1.21

special emergency equipment during the scanning procedure, or necessitate any other precautions.

Generally, standard screening forms (APPENDIX 1) are used for all patients scanned in a magnetic resonance system.

The presence of any ferromagnetic metals may be a health hazard to the patient when he or she is inside the magnet, and will also affect the imaging. If in doubt as to the exact composition of the items, it is best to exclude patients with any metal implants; see Shellock (1996) for discussion of what implants may be safely scanned using magnetic resonance.

Patients may be accompanied into the magnet room by a friend or family member, who can sit in the room during the scan and comfort the patient as needed. This companion must be screened as well to ensure the absence of loose metal objects on the body or clothing.

2. If the procedure is a research protocol, have the patient sign any necessary consent forms.

3. Have the patient remove all jewelry and change into a gown to eliminate any metal that might be found in clothing.

4. Have the patient wash off any mascara and other makeup to avoid local tissue heating and image artifacts.

5. Inform the patient about what will occur during the procedure, what he or she will experience while in the magnet, and how to behave, including the following:

   a. If earphones or headphones are used to protect the ears from the loud sounds produced by the gradients, the patient will be asked to wear these, but will be able to communicate with you at any time during the imaging.
   b. The patient will be given a safety squeeze-bulb or similar equipment to request assistance at any time (demonstrate how this works).
   c. For good results, the patient may breathe in a normal, relaxed manner but should avoid or minimize any other movement during each scan, i.e., as long as the banging sounds continue. Between scans, the patient should not change the position of the region of the body being imaged.
   d. Nevertheless, the patient may call out at any time if he or she feels it necessary.

6. Have the patient lie on the table in the supine position.

7. Position the extremity coil around the symptomatic calf.

   Have the patient point with one finger to the area of most intense pain and place a marker on this point. Center the coil about the marker. If the point of pain is extremely superior or inferior, the coil may be placed such that the superior or inferior half of the tibia is covered.

8. If needed, place a pillow or other support under the knees to make the patient more comfortable.

9. Use the laser light to point the center of the coil and put the patient into the center of the magnet.

   Once this step has been performed, so long as the patient does not move on the table, the table itself can be moved and then replaced in the same position as before without jeopardizing the positioning of one scan relative to another.

10. If the patient is unable to hold still, provide an appropriate sedative.

Sequence 1: Coronal T_1-weighted spin echo

11. Access the spin echo sequence on the system console and set the imaging parameters as shown in Table A24.1.2.
12. Inform the patient that the scan is about to begin.
13. Start the scan.

This sequence also serves as the scout scan. A separate scout sequence is not necessary. Care should be taken that imaging is performed through the entire antero-posterior dimension of the calf.

Table A24.1.2 Tibial Stress Injuries: Imaging Parameters for Sequence 1

Patient position	Supine
Scan type	Spin echo
Imaging plane (orientation)	Coronal
Central slice or volume center	Centered on antero-posterior center of the calf
Echo time (T_E)	"Minimum full" (usually ~15 msec)
Repeat time (T_R)	600 msec
Flip angle (FA)	90°
Fields of view (FOV_x, FOV_y)	160–200 mm, 160–200 mm
Resolution (Δx, Δy)	0.31–0.39 mm, 0.83–1.04 mm
Number of data points collected (N_x, N_y)	512, 192
Display matrix (D_x, D_y)	512, 512
Slice thickness (Δz)	4 mm
Number of slices	Variable (enough to cover the entire tibia from anterior to posterior)
Slice gap	1 mm
Number of acquisitions (N_{acq})	2
Saturation pulses	None
Scan time	3 min, 54 sec

Table A24.1.3 Tibial Stress Injuries: Imaging Parameters for Sequence 2

Patient position	Supine
Scan type	Fast spin echo
Imaging plane (orientation)	Coronal
Central slice or volume center	Centered on antero-posterior center of the calf
Echo time (T_E)	70 msec
Echo train length (ETL)	8
Repeat time (T_R)	4000 msec
Flip angle (FA)	90°
Fields of view (FOV_x, FOV_y)	160–200 mm, 160–200 mm
Resolution (Δx, Δy)	0.31–0.39 mm, 0.83–1.04 mm
Number of data points collected (N_x, N_y)	512, 192
Display matrix (D_x, D_y)	512, 512
Slice thickness (Δz)	4 mm
Number of slices	Variable (enough to cover the entire tibia from anterior to posterior)
Slice gap	1 mm
Number of acquisitions (N_{acq})	2
Saturation pulses	Frequency-selective fat saturation
Scan time	3 min, 28 sec

Table A24.1.4 Tibial Stress Injuries: Imaging Parameters for Sequence 3

Patient position	Supine
Scan type	Spin echo
Imaging plane (orientation)	Transverse
Central slice or volume center	Centered on the marker
Echo time (T_E)	"Minimum full" (usually ~15 msec)
Repeat time (T_R)	600 msec
Flip angle (FA)	90°
Fields of view (FOV_x, FOV_y)	140–180 mm, 140–180 mm (as small as possible but including the entire calf diameter)
Resolution (Δx, Δy)	0.27–0.35 mm, 0.73–0.94 mm
Number of data points collected (N_x, N_y)	512, 192
Display matrix (D_x, D_y)	512, 512
Slice thickness (Δz)	4 mm
Number of slices	~32–40 (image 8–10 cm approximately and same distance distal to the point of maximum tenderness as indicated by the point)
Slice gap	1 mm
Number of acquisitions (N_{acq})	2
Saturation pulses	None
Scan time	3 min, 54 sec

Table A24.1.5 Tibial Stress Injuries: Imaging Parameters for Sequence 4

Patient position	Supine
Scan type	Fast spin echo
Imaging plane (orientation)	Transverse
Central slice or volume center	Centered on the marker
Echo time (T_E)	70 msec
Echo train length (ETL)	8
Repeat time (T_R)	4150 msec
Flip angle (FA)	90°
Fields of view (FOV_x, FOV_y)	140–180 mm, 140–180 mm (as small as possible but including the entire calf diameter)
Resolution (Δx, Δy)	0.27–0.35 mm, 0.73–0.94 mm
Number of data points collected (N_x, N_y)	512, 192
Display matrix (D_x, D_y)	512, 512
Slice thickness (Δz)	4 mm
Number of slices	~32–40 (image 8–10 cm approximately and same distance distal to the point of maximum tenderness as indicated by the point)
Slice gap	1 mm
Number of acquisitions (N_{acq})	2
Saturation pulses	Frequency-selective fat saturation
Scan time	3 min, 36 sec

Sequence 2: Coronal T_2-weighted fast spin echo (FSE)

14. Call up the menu for the fast spin echo sequence on the console. Use the parameters seen in Table A24.1.3.

15. Run the sequence.

Sequence 3: Transverse T_1-weighted spin echo

16. Once again go to the spin echo sequence on the system console and set the imaging parameters as shown in Table A24.1.4.

17. Instruct the patient to remain still and run scan.

Sequence 4: Transverse T_2-weighted fast spin echo

18. Set up for a fast spin echo scan using the parameters outlined in Table A24.1.5.

19. Run the sequence.

FEMORAL NECK AND FEMORAL SHAFT STRESS INJURIES

BASIC PROTOCOL 2

Stress fractures of the femur are relatively common injuries in which MR imaging can be extremely useful. Femoral neck stress injuries deserve special attention. They can progress to displaced fractures with associated complications such as avascular necrosis and irreversible joint damage if not promptly diagnosed and properly treated. MRI is more sensitive than radiography and more specific than radionuclide bone scan in evaluation of proximal femoral abnormalities (Shin et al., 1996). It allows for differentiation between stress fracture and other causes of hip pain such as avascular necrosis, symptomatic synovial herniation pit, iliopsoas bursitis, iliopsoas or obturator externus tendinitis, or iliopsoas muscle tear (Bergman and Fredericson, 1999).

MR imaging is also useful in the evaluation of possible femoral diaphyseal injuries. Stress fractures in this location may commonly be misdiagnosed as muscle injuries (Bergman and Fredericson, 1999). MRI, by evaluating both the bone and soft tissues, is effective in differentiating these abnormalities.

Optimal evaluation of the femur includes T_1- and T_2-weighted imaging in the coronal (Figures A24.1.1 through A24.1.4) and transverse planes. This protocol requires ~30 min to complete.

Sequence 5: Coronal T_1-weighted spin echo

1. Screen and prepare the patient as described in Basic Protocol 1, steps 1 to 6.

2. With the patient in the supine position, center the phased array or torso (not extremity) coil at the level of the greater trochanter if femoral neck fracture suspected or at the level of maximum pain if the femoral shaft is the area of interest. For the coronal sequences, include both femurs in the field of view. Place a marker at the area of maximum pain. Repeat Basic Protocol 1, steps 8 to 10.

3. Run the scan according to the imaging parameters listed in Table A24.1.6.

   This sequence also serves as the scout scan. A separate scout sequence is not necessary. Care should be taken that imaging is performed through the entire antero-posterior dimension of the thigh.

Sequence 6: Coronal T_2-weighted fast spin echo

4. Scan the patient according to the parameters in Table A24.1.7.

Figure A24.1.1 T_1-weighted coronal image of the pelvis and proximal femurs in a 17-year-old distance runner with a femoral neck stress fracture.

Figure A24.1.2 T_2-weighted coronal image of the pelvis and proximal femurs in a 17-year-old distance runner with a femoral neck stress fracture.

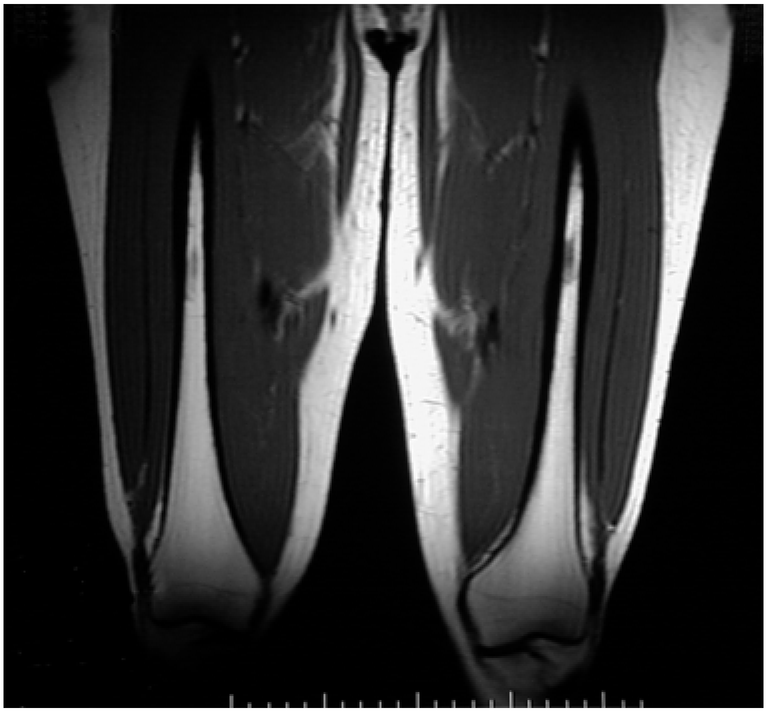

Figure A24.1.3 T_1-weighted coronal image of the pelvis and proximal femurs in a 37-year-old distance runner with a femoral diaphyseal stress fracture.

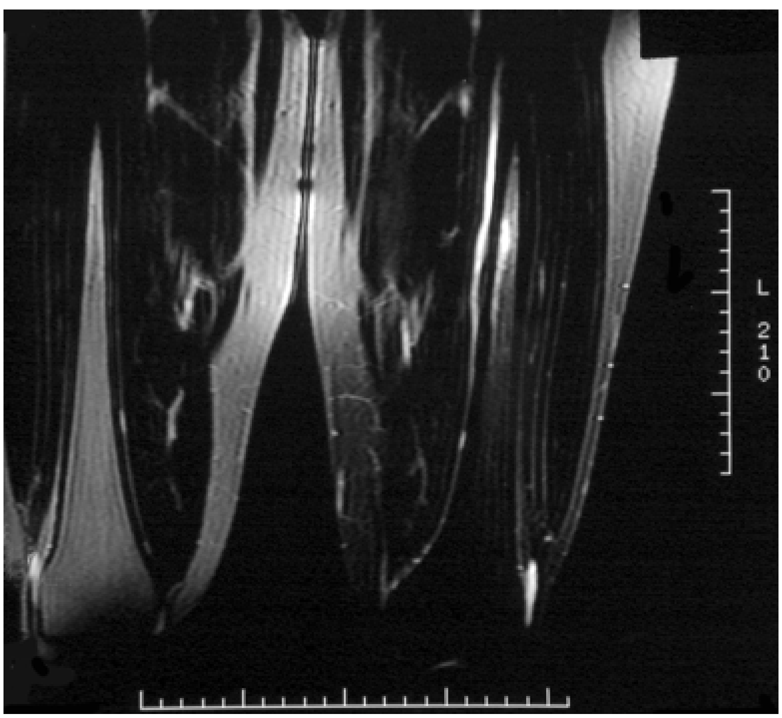

Figure A24.1.4 T_2-weighted coronal image of the pelvis and proximal femurs in a 37-year-old distance runner with a femoral diaphyseal stress fracture.

Table A24.1.6 Femoral Stress Injuries: Imaging Parameters for Sequence 5

Patient position	Supine
Scan type	Spin echo
Imaging plane (orientation)	Coronal
Central slice or volume center	Centered antero-posteriorly on the greater trochanter (femoral neck fracture) or femoral shaft (diaphyseal fracture)
Echo time (T_E)	“Minimum full” (usually ~15 msec)
Repeat time (T_R)	600 msec
Flip angle (FA)	90°
Fields of view (FOV_x, FOV_y)	320 mm, 320 mm
Resolution (Δx, Δy)	0.63 mm, 1.67 mm
Number of data points collected (N_x, N_y)	512, 192
Display matrix (D_x, D_y)	512, 512
Slice thickness (Δz)	4 mm
Number of slices	Variable (enough to cover the entire thigh from anterior to posterior)
Slice gap	1 mm
Number of acquisitions (N_{acq})	2
Saturation pulses	None
Scan time	3 min, 54 sec

Table A24.1.7 Femoral Stress Injuries: Imaging Parameters for Sequence 6

Patient position	Supine
Scan type	Fast spin echo
Imaging plane (orientation)	Coronal
Central slice or volume center	Centered antero-posteriorly on the greater trochanter (femoral neck fracture) or femoral shaft (diaphyseal fracture)
Echo time (T_E)	70 msec
Echo train length (ETL)	8
Repeat time (T_R)	4000 msec
Flip angle (FA)	90°
Fields of view (FOV_x, FOV_y)	320 mm, 320 mm
Resolution (Δx, Δy)	0.63 mm, 1.67 mm
Number of data points collected (N_x, N_y)	512, 192
Display matrix (D_x, D_y)	512, 512
Slice thickness (Δz)	4 mm
Number of slices	Variable (enough to cover the entire thigh from anterior to posterior)
Slice gap	1 mm
Number of acquisitions (N_{acq})	2
Saturation pulses	Frequency-selective fat saturation
Scan time	3 min, 44 sec

Table A24.1.8 Femoral Stress Injuries: Imaging Parameters for Sequence 7

Patient position	Supine
Scan type	Spin echo
Imaging plane (orientation)	Transverse
Central slice or volume center	Centered on the greater trochanter or the marker
Echo time (T_E)	“Minimum full” (usually ~15 msec)
Repeat time (T_R)	600 msec
Flip angle (FA)	90°
Fields of view (FOV_x, FOV_y)	200–240 mm, 200–240 mm (as small as possible)
Resolution (Δx, Δy)	0.39–0.47 mm, 1.04–1.25 mm
Number of data points collected (N_x, N_y)	512, 192
Display matrix (D_x, D_y)	512, 512
Slice thickness (Δz)	4 mm
Number of slices	~32–40 (see Table A24.1.4)
Slice gap	1 mm
Number of acquisitions (N_{acq})	2
Saturation pulses	None
Scan time	7 min, 48 sec

Table A24.1.9 Femoral Stress Injuries: Imaging Parameters for Sequence 8

Patient position	Supine
Scan type	Fast spin echo
Imaging plane (orientation)	Transverse
Central slice or volume center	Centered on the greater trochanter or the marker
Echo time (T_E)	70 msec
Echo train length (ETL)	8
Repeat time (T_R)	4000 msec
Flip angle (FA)	90°
Fields of view (FOV_x, FOV_y)	200–240 mm, 200–240 mm (as small as possible)
Resolution (Δx, Δy)	0.39–0.47 mm, 1.04–1.25 mm
Number of data points collected (N_x, N_y)	512, 192
Display matrix (D_x, D_y)	512, 512
Slice thickness (Δz)	4 mm
Number of slices	~32–40 (see Table A24.1.4)
Slice gap	1 mm
Number of acquisitions (N_{acq})	2
Saturation pulses	Frequency-selective fat saturation
Scan time	7 min, 12 sec

Sequence 7: Transverse T_1-weighted spin echo

5. Perform scan in the transverse plane according to the parameters in Table A24.1.8.

Sequence 8: Transverse T_2-weighted fast spin echo

6. Run the scan in the transverse plane according to the parameters in Table A24.1.9.

BASIC PROTOCOL 3

IMAGING OF METATARSAL STRESS INJURIES

Metatarsal stress fractures or "march fractures" are commonly seen in military recruits. They most often occur in the distal diaphyses of the second and third metatarsals. Although radiography and bone scanning can be useful in these patients, MR imaging demonstrates evidence of stress injury and stress fracture well. These are not critical fractures and activity can usually be resumed as soon as there is no pain with ambulation.

Imaging of these injuries is performed with T_1- and T_2-weighted sequences the coronal, sagittal, and transverse planes (Figures A24.1.5 to A24.1.7). The authors prefer to use an inversion recovery (IR) FSE technique as the T_2-weighted sequence in this region. Suppression of fat signal with this sequence is superior to the standard T_2-weighted FSE with fat saturation because it is not affected by the local magnetic field inhomogeneity in the region of the foot. This protocol requires ~40 min to complete.

Sequence 9: Coronal T_1-weighted spin echo

1. Screen and prepare the patient as described in Basic Protocol 1, steps 1 to 6.
2. Position the extremity coil with the center over the symptomatic forefoot. Repeat Basic Protocol 1, steps 8 to 10.
3. Run the scan according to the parameters in Table A24.1.10.

   This sequence also serves as the scout scan. A separate scout sequence is not necessary. Care should be taken that imaging is performed through the entire antero-posterior dimension of the foot.

   Note that the foot is usually best positioned with a right angle at the ankle, as if standing up with the full planar surface on the ground (not with a pointed foot). With the foot in that position, the imaging planes (transverse, coronal, and sagittal) of the foot will be the same as in the body, projected down to the foot (see Figure A24.1.8).

Sequence 10: Coronal T_2-weighted inversion recovery fast spin echo

4. Run the scan according to the parameters in Table A24.1.11.

Sequence 11: Sagittal T_1-weighted spin echo

5. Scan the patient in the sagittal plane according to the parameters in Table A24.1.12.

Sequence 12: Sagittal T_2-weighted inversion recovery fast spin echo

6. Scan in the sagittal plane according to the parameters in Table A24.1.13.

Sequence 13: Transverse T_1-weighted spin echo

7. Perform scan in the transverse plane according to the parameters in Table A24.1.14.

Sequence 14: Transverse T_2-weighted inversion recovery fast spin echo

8. Perform another scan in the transverse plane according to the parameters in Table A24.1.15.

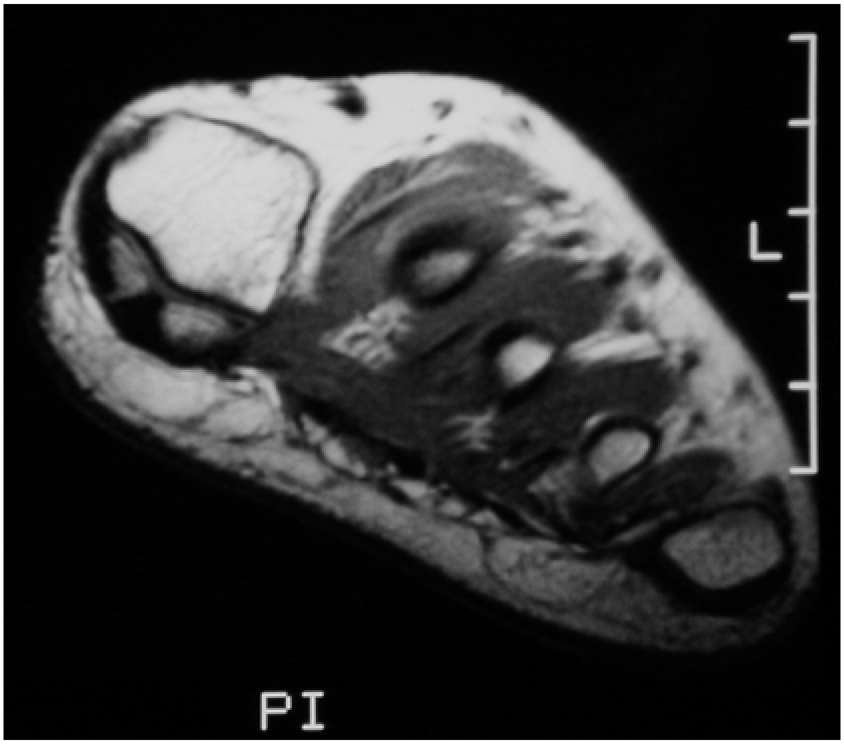

Figure A24.1.5 T_1-weighted coronal image of the foot in a patient with a metatarsal stress fracture.

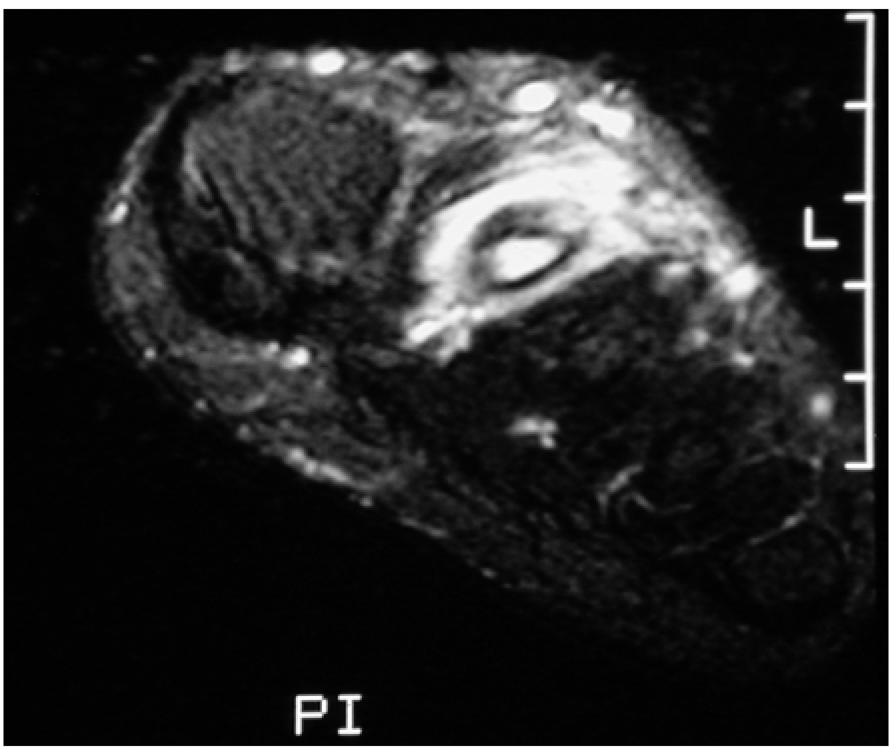

Figure A24.1.6 T_2-weighted coronal image of the foot in a patient with a metatarsal stress fracture.

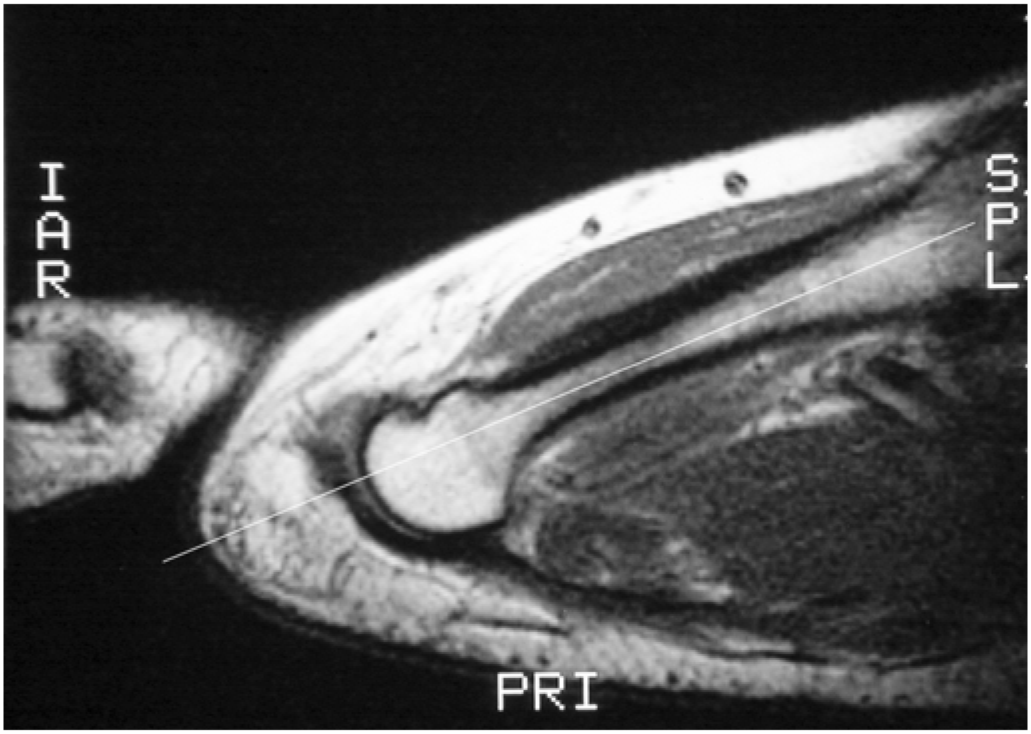

Figure A24.1.7 T_1-weighted sagittal image of the foot in a patient with a metatarsal stress fracture.

Table A24.1.10 Metatarsal Stress Injuries: Imaging Parameters for Sequence 9

Patient position	Supine
Scan type	Spin echo
Imaging plane (orientation)	Coronal
Central slice or volume center	Centered on the antero-posterior midpoint of the forefoot
Echo time (T_E)	"Minimum full" (usually ~15 msec)
Repeat time (T_R)	600 msec
Flip angle (FA)	90°
Fields of view (FOV_x, FOV_y)	160–200 mm, 160–200 mm
Resolution (Δx, Δy)	0.31–0.39 mm, 0.83–1.04 mm
Number of data points collected (N_x, N_y)	512, 192
Display matrix (D_x, D_y)	512, 512
Slice thickness (Δz)	4 mm
Number of slices	Variable
Slice gap	1 mm
Number of acquisitions (N_{acq})	2
Saturation pulses	None
Scan time	3 min, 54 sec

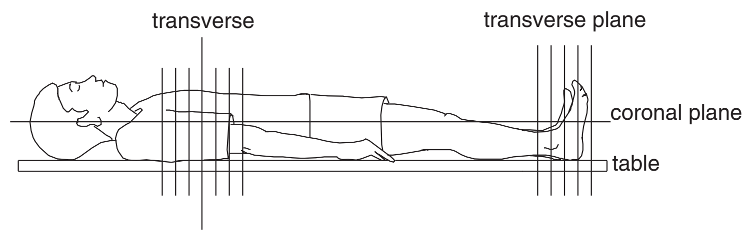

Figure A24.1.8 With the foot positioned at right angle to the body, the transverse and coronal planes as used in this text are in the same orientation as in the body.

Table A24.1.11 Metatarsal Stress Injuries: Imaging Parameters for Sequence 10

Patient position	Supine
Scan type	Inversion recovery fast spin echo
Imaging plane (orientation)	Coronal
Central slice or volume center	Centered on the antero-posterior midpoint of the forefoot
Echo time (T_E)	60 msec
Echo train length (ETL)	8
Repeat time (T_R)	6200 msec
Inversion time (T_I)	160 msec
Flip angle (FA)	90°
Fields of view (FOV_x, FOV_y)	160–200 mm, 160–200 mm
Resolution (Δx, Δy)	0.31–0.39 mm, 0.83–1.04 mm
Number of data points collected (N_x, N_y)	512, 192
Display matrix (D_x, D_y)	512, 512
Slice thickness (Δz)	4 mm
Number of slices	~20–30
Slice gap	1 mm
Number of acquisitions (N_{acq})	1
Saturation pulses	Inversion recovery fat suppression
Scan time	5 min, 23 sec

Table A24.1.12 Metatarsal Stress Injuries: Imaging Parameters for Sequence 11

Patient position	Supine
Scan type	Spin echo
Imaging plane (orientation)	Sagittal
Central slice or volume center	Centered on the third metatarsal
Echo time (T_E)	"Minimum full" (usually ~15 msec)
Repeat time (T_R)	650 msec
Flip angle (FA)	90°
Fields of view (FOV_x, FOV_y)	160–200 mm, 160–200 mm
Resolution (Δx, Δy)	0.31–0.39 mm, 0.83–1.04 mm
Number of data points collected (N_x, N_y)	512, 192
Display matrix (D_x, D_y)	512, 512
Slice thickness (Δz)	3 mm
Number of slices	Variable
Slice gap	1 mm
Number of acquisitions (N_{acq})	2
Saturation pulses	None
Scan time	4 min, 14 sec

Table A24.1.13 Metatarsal Stress Injuries: Imaging Parameters for Sequence 12

Patient position	Supine
Scan type	Inversion recovery fast spin echo
Imaging plane (orientation)	Sagittal
Central slice or volume center	Centered on the third metatarsal
Echo time (T_E)	60 msec
Echo train length (ETL)	8
Repeat time (T_R)	6200 msec
Inversion time (T_I)	160 msec
Flip angle (FA)	90°
Fields of view (FOV_x, FOV_y)	160–200 mm, 160–200 mm
Resolution (Δx, Δy)	0.31–0.39 mm, 0.83–1.04 mm
Number of data points collected (N_x, N_y)	512, 192
Display matrix (D_x, D_y)	512, 512
Slice thickness (Δz)	3 mm
Number of slices	~20–25
Slice gap	1 mm
Number of acquisitions (N_{acq})	1
Saturation pulses	Inversion recovery fat suppression
Scan time	8 min, 40 sec

Table A24.1.14 Metatarsal Stress Injuries: Imaging Parameters for Sequence 13

Patient position	Supine
Scan type	Spin echo
Imaging plane (orientation)	Transverse (parallel to metatarsal long axis)
Central slice or volume center	Centered on the supero-inferior center of the metatarsals
Echo time (T_E)	"Minimum full" (usually ~15 msec)
Repeat time (T_R)	600 msec
Flip angle (FA)	90°
Fields of view (FOV_x, FOV_y)	160–200 mm, 160–200 mm
Resolution (Δx, Δy)	0.31–0.39 mm, 0.83–1.04 mm
Number of data points collected (N_x, N_y)	512, 192
Display matrix (D_x, D_y)	512, 512
Slice thickness (Δz)	3 mm
Number of slices	Variable
Slice gap	1 mm
Number of acquisitions (N_{acq})	2
Saturation pulses	None
Scan time	3 min, 54 sec

Table A24.1.15 Metatarsal Stress Injuries: Imaging Parameters for Sequence 14

Patient position	Supine
Scan type	Inversion recovery fast spin echo
Imaging plane (orientation)	Transverse (parallel to metatarsal long axis)
Central slice or volume center	Centered on the supero-inferior center of the metatarsals
Echo time (T_E)	60 msec
Echo train length (ETL)	8
Repeat time (T_R)	5000 msec
Inversion time (T_I)	160 msec
Flip angle (FA)	90°
Fields of view (FOV_x, FOV_y)	160–200 mm, 160–200 mm
Resolution (Δx, Δy)	0.31–0.39 mm, 0.83–1.04 mm
Number of data points collected (N_x, N_y)	512, 192
Display matrix (D_x, D_y)	512, 512
Slice thickness (Δz)	3 mm
Number of slices	Variable
Slice gap	1 mm
Number of acquisitions (N_{acq})	2
Saturation pulses	Inversion recovery fat suppression
Scan time	4 min, 20 sec

IMAGING OF NAVICULAR STRESS INJURIES

BASIC PROTOCOL 4

MR imaging is often essential in the identification of navicular stress fractures. Radiographs are not as sensitive as MRI for the early detection of this injury, which can be debilitating if not diagnosed promptly (Khan et al., 1994; Pavlov et al., 1983). They may be treated surgically or nonsurgically depending on the degree of displacement.

T_1- and T_2-weighted images are obtained in three planes (Figures A24.1.9 and A24.1.10). IR FSE technique is again preferred for the T_2-weighted sequences because of superior suppression of fat signal in this area of local magnetic field inhomogeneity. This protocol may require ~40 min to complete.

Sequence 15: Coronal T_1-weighted spin echo

1. Screen and prepare the patient as described in Basic Protocol 1, steps 1 to 6.
2. Place the extremity coil on the symptomatic foot with the center over the hindfoot. Repeat Basic Protocol 1, steps 8 to 10.
3. Perform a coronal scan according to the parameters in Table A24.1.16.

   This sequence also serves as the scout scan. A separate scout sequence is not necessary. Care should be taken that imaging is performed through the entire antero-posterior dimension of the foot.

Sequence 16: Coronal T_2-weighted inversion recovery fast spin echo

4. Perform a coronal scan according to the parameters in Table A24.1.17.

Sequence 17: Sagittal T_1-weighted spin echo

5. Scan the patient in the sagittal plane according to the parameters in Table A24.1.18.

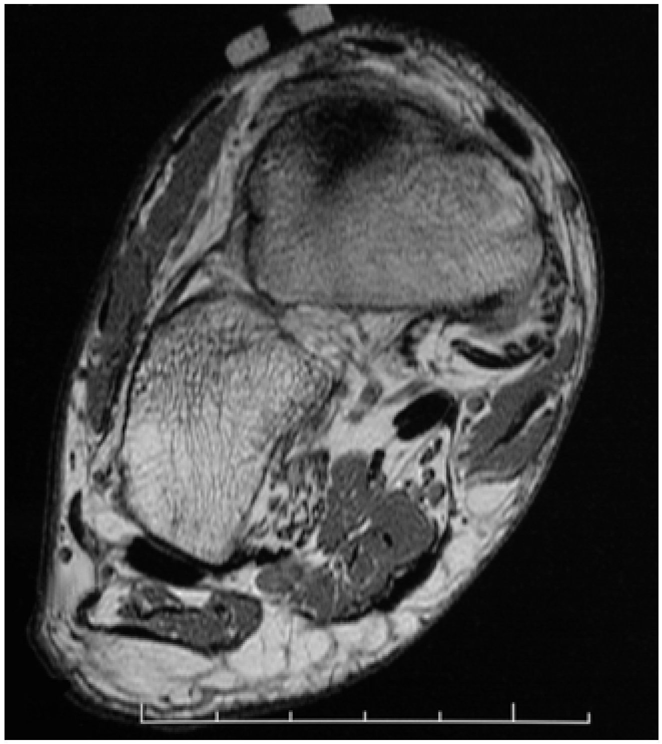

Figure A24.1.9 T_1-weighted coronal image in a 19-year-old distance runner with a navicular stress fracture.

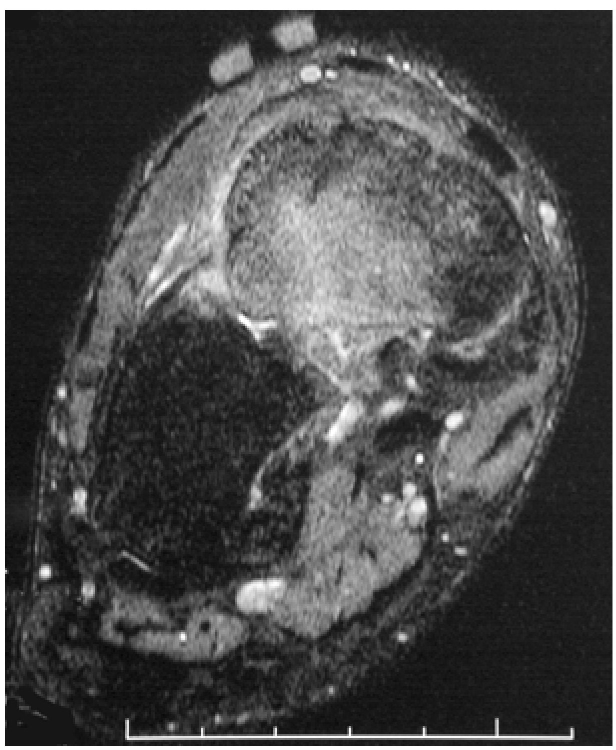

Figure A24.1.10 T_2-weighted coronal image in a 19-year-old distance runner with a navicular stress fracture.

Table A24.1.16 Navicular Stress Injuries: Imaging Parameters for Sequence 15

Patient position	Supine
Scan type	Spin echo
Imaging plane (orientation)	Coronal
Central slice or volume center	Centered on the antero-posterior midpoint of the hindfoot
Echo time (T_E)	"Minimum full" (usually ~15 msec)
Repeat time (T_R)	500 msec
Flip angle (FA)	90°
Fields of view (FOV_x, FOV_y)	160–200 mm, 160–200 mm
Resolution (Δx, Δy)	0.31–0.39 mm, 0.83–1.04 mm
Number of data points collected (N_x, N_y)	512, 192
Display matrix (D_x, D_y)	512, 512
Slice thickness (Δz)	3 mm
Number of slices	~25
Slice gap	1 mm
Number of acquisitions (N_{acq})	2
Saturation pulses	None
Scan time	6 min, 32 sec

Table A24.1.17 Navicular Stress Injuries: Imaging Parameters for Sequence 16

Patient position	Supine
Scan type	Inversion recovery fast spin echo
Imaging plane (orientation)	Coronal
Central slice or volume center	Centered on the antero-posterior midpoint of the hindfoot
Echo time (T_E)	60 msec
Echo train length (ETL)	8
Repeat time (T_R)	5000 msec
Inversion time (T_I)	160 msec
Flip angle (FA)	90°
Fields of view (FOV_x, FOV_y)	160–200 mm, 160–200 mm
Resolution (Δx, Δy)	0.31–0.39 mm, 0.83–1.04 mm
Number of data points collected (N_x, N_y)	512, 192
Display matrix (D_x, D_y)	512, 512
Slice thickness (Δz)	3 mm
Number of slices	~25
Slice gap	1 mm
Number of acquisitions (N_{acq})	2
Saturation pulses	Inversion recovery fat suppression
Scan time	8 min, 40 sec

Table A24.1.18 Navicular Stress Injuries: Imaging Parameters for Sequence 17

Patient position	Supine
Scan type	Spin echo
Imaging plane (orientation)	Sagittal
Central slice or volume center	Centered on the medio-lateral center of the hindfoot
Echo time (T_E)	"Minimum full" (usually ~15 msec)
Repeat time (T_R)	650 msec
Flip angle (FA)	90°
Fields of view (FOV_x, FOV_y)	160–200 mm, 160–200 mm
Resolution (Δx, Δy)	0.31–0.39 mm, 0.83–1.04 mm
Number of data points collected (N_x, N_y)	512, 192
Display matrix (D_x, D_y)	512, 512
Slice thickness (Δz)	3 mm
Number of slices	Variable
Slice gap	1 mm
Number of acquisitions (N_{acq})	2
Saturation pulses	None
Scan time	4 min, 14 sec

Table A24.1.19 Navicular Stress Injuries: Imaging Parameters for Sequence 18

Patient position	Supine
Scan type	Inversion recovery fast spin echo
Imaging plane (orientation)	Sagittal
Central slice or volume center	Centered on the medio-lateral center of the hindfoot
Echo time (T_E)	60 msec
Echo train length (ETL)	8
Repeat time (T_R)	5000 msec
Inversion time (T_I)	160 msec
Flip angle (FA)	90°
Fields of view (FOV_x, FOV_y)	160–200 mm, 160–200 mm
Resolution (Δx, Δy)	0.31–0.39 mm, 0.83–1.04 mm
Number of data points collected (N_x, N_y)	512, 192
Display matrix (D_x, D_y)	512, 512
Slice thickness (Δz)	3 mm
Number of slices	~20–25
Slice gap	1 mm
Number of acquisitions (N_{acq})	2
Saturation pulses	Inversion recovery fat suppression
Scan time	8 min, 40 sec

Table A24.1.20 Navicular Stress Injuries: Imaging Parameters for Sequence 19

Patient position	Supine
Scan type	Spin echo
Imaging plane (orientation)	Transverse
Central slice or volume center	Centered on the supero-inferior center of the hindfoot
Echo time (T_E)	"Minimum full" (usually ~15 msec)
Repeat time (T_R)	650 msec
Flip angle (FA)	90°
Fields of view (FOV_x, FOV_y)	160–200 mm, 160–200 mm
Resolution (Δx, Δy)	0.31–0.39 mm, 0.83–1.04 mm
Number of data points collected (N_x, N_y)	512, 192
Display matrix (D_x, D_y)	512, 512
Slice thickness (Δz)	3 mm
Number of slices	Variable
Slice gap	1 mm
Number of acquisitions (N_{acq})	2
Saturation pulses	None
Scan time	4 min, 14 sec

Table A24.1.21 Navicular Stress Injuries: Imaging Parameters for Sequence 20

Patient position	Supine
Scan type	Inversion recovery fast spin echo
Imaging plane (orientation)	Transverse
Central slice or volume center	Centered on the supero-inferior center of the hindfoot
Echo time (T_E)	60 msec
Echo train length (ETL)	8
Repeat time (T_R)	5000 msec
Inversion time (T_I)	160 msec
Flip angle (FA)	90°
Fields of view (FOV_x, FOV_y)	160–200 mm, 160–200 mm
Resolution (Δx, Δy)	0.31–0.39 mm, 0.83–1.04 mm
Number of data points collected (N_x, N_y)	512, 192
Display matrix (D_x, D_y)	512, 512
Slice thickness (Δz)	3 mm
Number of slices	~20–25
Slice gap	1 mm
Number of acquisitions (N_{acq})	2
Saturation pulses	Inversion recovery fat suppression
Scan time	8 min, 40 sec

Sequence 18: Sagittal T_2-weighted inversion recovery fast spin echo

6. Run the scan according to the parameters in Table A24.1.19.

Sequence 19: Transverse T_1-weighted spin echo

7. Scan the patient according to the parameters in Table A24.1.20.

Sequence 20: Transverse T_2-weighted inversion recovery fast spin echo

8. Perform the scan in the transverse plane according to the parameters in Table A24.1.21.

COMMENTARY

Background Information

Musculoskeletal stress injuries are among the most commonly encountered sports medicine conditions, with stress fractures accounting for ~10% of visits to sports medicine clinics (Matheson et al., 1987). Bone stress injuries represent a spectrum of abnormalities ranging from early stress reaction to frank cortical fracture. They often present a diagnostic challenge for clinicians as differentiation between the more benign stress reactions (such as shin splint syndrome in the tibia) and more advanced stress injury or fracture can be difficult. As this point of distinction is essential to the proper management of these patients, the ability of MR grading of stress lesion severity has proven to be clinically useful (Lee and Yao, 1988; Bergman and Fredericson, 1999).

Bony stress lesions develop when an area of accelerated bone remodeling occurs in response to repetitive stress. Bone resorption is greater than new bone formation in this region, leading to bone weakening and eventually to trabecular microfractures (stress injury). With further activity, a full cortical break or stress fracture can occur (Daffner and Pavlov, 1992).

The location of injury depends on the activity undertaken by the patient as well as other biomechanical factors. For example, runners often develop injuries in the tibia, the femoral neck or diaphysis, or the navicular bone (Daffner and Pavlov, 1992). Much overlap exists however.

Stress injuries usually present as focal pain that begins during the end of an exercise session or soon afterwards. Eventually, the pain occurs throughout the exercise period and then during other daily activities as well. On physical examination, tenderness and swelling are noted over the affected area on direct palpation.

While radiography remains the initial test in screening individuals with possible stress injuries, it is negative in two thirds of patients at the onset of symptoms and remains negative in approximately one half of these patients (Floyd et al., 1987). Radionuclide bone scanning (bone scintigraphy) is an alternative test that is more effective than radiography at detecting early stress injury. A progression of bone scan findings has been associated with corresponding evolution of stress injury. Bone scans demonstrate diffuse uptake with an early stress reaction, and more focal and intense uptake with a stress fractures (Roub et al., 1979).

However, MR imaging is superior to bone scintigraphy in several respects. Unlike MRI, bone scans do not effectively evaluate the surrounding soft tissues. As a result, unsuspected soft tissue injuries can be missed. In addition, a positive bone scan finding is not specific for stress injury (Shin et al., 1996). Because a bone scan simply indicates areas of increased new bone formation, other conditions can mimic fractures. Finally, Milgrom et al. (1984) suggest that a negative bone scan does not always exclude a stress injury.

Critical Parameters and Troubleshooting

Although MR imaging can detect stress injuries causing frank cortical fractures, it is most useful in diagnosing more subtle injuries. For this, accurate detection of even very subtle periosteal and bone marrow edema is essential for this function. Thus, the authors propose that high magnetic field strength systems should be used for this examination, as they are superior in this regard.

In addition, use of T_2-weighted sequences that provide optimal fat signal suppression is also important so that false positive results are not obtained. In the femurs and tibias, T_2-weighted FSE sequences with a fat saturation pulse perform well and have greater signal-to-noise than IR FSE sequences. However, in regions with significant local magnetic field inhomogeneity such as the ankle and foot, the superiority of the fat signal suppression with the IR FSE sequence outweighs its signal-to-noise deficiency.

Maximum resolution is desired so that small areas of edema are not missed. An extremity coil is almost always preferred for this reason. If the patient has bilateral symptoms, a torso phased array or body coil may be used initially, then with additional scans using an extremity coil to follow, if an area of abnormality is identified. It is also important to center the imaging on the site of maximal pain by having the patient point to the area with one finger and to position him or her accordingly. To further maximize the resolution, the acquisition matrix (N_x, N_y) should be set to N_x = 512 in the frequency dimension, if practical.

Anticipated Results

Magnetic resonance imaging (MRI) is considered by many to be the imaging modality of choice for the evaluation of bone stress injuries. It provides a means of making an early diagnosis, and allowing appropriate treatment to be initiated by accurately staging the lesions. T_2-weighted imaging is most sensitive for the detection of bone marrow and periosteal edema, which are early signs of bone stress injury. T_1-weighted images are also helpful, in grading stress injuries and in visualization of cortical fracture lines. A grading system for tibial stress injuries has been outlined by Fredericson et al. (1995). Early stress reaction (Grade 1) is represented by abnormal periosteal signal on T_2-weighted images (periosteal edema). As the injury progresses (Grade 2), bone marrow edema is demonstrated on T_2-weighted images. Grade 3 images are seen as marrow and periosteal edema on both T_2-weighted and T_1-weighted imaging. Finally, if a low signal fracture line is present on both images, the injury is classified as Grade 4. Similar findings can be seen in stress injuries of other bones.

Classification of stress injuries is important so that appropriate steps to treatment may be taken. For example, tibial Grade 1 and 2 injuries may be treated with a rest period varying from 2 to 6 weeks. Grade 3 injuries often require longer periods of rest, and Grade 4 injuries may need nonweightbearing, casting, or sometimes surgery depending on location. All stages may progress if improperly or incompletely treated, sometimes with catastrophic long-term results.

Literature Cited

Bergman, A.G. and Fredericson, M. 1999. MR imaging of stress reactions, muscle injuries, and other overuse injuries in runners. *MRI Clinics of North America.* 7:151-174.

Daffner, R.H. and Pavlov H. 1992. Stress fractures: Current concepts. *A.J.R.. Am. J. Roentgenol.* 159:245-252.

Floyd, W.N., Butler J.E., Clanton T., Kim, E.E., and Pjura, G. 1987. Roentgenologic diagnosis of stress fractures and stress reactions. *South. Med. J.* 80:433-439.

Fredericson, M., Bergman, A.G., Hoffman, K.L., and Dillingham, M.S. 1995. Tibial stress reaction in runners: Correlation of clinical symptoms and scintigraphy with a new magnetic resonance imaging grading system. *Am. J. Sports Med.* 23:472-481.

Hulkko, A. and Orava, S. 1987. Stress fractures in athletes. *Int. J. Sports Med.* 8:221-226.

Khan, K.M., Brukner, P.D., and Kearney, C. 1994. Tarsal navicular stress fracture in athletes. *Sports Med.* 17:65-76.

Lee, J.K. and Yao, L. 1988. Stress fractures: MR imaging. *Radiology* 169:217-220.

Matheson, G.O., Clement, D.B., McKenzie, D.C., Taunton, J.E., Lloyd-Smith, D.R., and MacIntyre, J.G. 1987. Stress fractures in athletes: a study of 320 cases. *Am. J. Sports Med.* 15:46-58.

Milgrom, C., Chisin, R., Giladi, M., Stein, M., Kashtan, H., Margulies, J., and Atlan, H. 1984. Negative bone scans in impending tibial stress fractures: A report of three cases. *Am. J. Sports Med.* 12: 488-491.

Pavlov, H., Torg, J.S., and Freiberger, R.H. 1983. Tarsal navicular stress fractures: Radiographic evaluation. *Radiology* 148:641-645.

Roub, L.W., Gumerman, L.W., and Hanley, E.N. 1979. Bone stress: A radionuclide imaging perspective. *Radiology* 132: 431-438.

Shellock, F.G. 1996. Pocket Guide to MR Procedures and Metallic Objects. Lippincott-Raven, Philadelphia.

Shin A.Y., Morin W.D., Gorman J.D., Jones, S.B., and Lapinsky, A.S.1996. The superiority of magnetic resonance imaging in differentiating the cause of hip pain in endurance athletes. *Am. J. Sports Med.* 24:168-176.

Contributed by Gabrielle Bergman and Timothy R. Jones
Stanford University Medical Center
Stanford, California